

The terminal bulk Lorentz factor of relativistic electron-positron jet

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Abstract: We present numerical simulation of bulk Lorentz factor of relativistic electron-positron jet driven by Compton rocket effect from accretion disk radiation. The plasma is assumed to have a power-law distribution $n_e(\gamma) \propto \gamma^{-s}$ ($1 < \gamma < \gamma_{max}$) and is continuously reheated to compensate radiation losses. We include Klein-Nishina (hereafter KN) corrections, and study the role of energy upper cut-off γ_{max} , spectral index s , and source compactness. We determine terminal bulk Lorentz factor in the case of supermassive black holes relevant to AGN and stellar black holes relevant to galactic microquasars. In the latter case, effects of KN corrections are more important, and induce terminal bulk Lorentz factor $\gamma_{b\infty}$ smaller than in the former case. The result can explain the low bulk Lorentz factors for galactic sources (GRS1915+105, GROJ1655-40) compared to extragalactic ones. We also take into account the influence of the size of the accretion disk; if the external radius is small enough, the bulk Lorentz factor can be as high as 60, which is comparable to the values needed to explain extragalactic gamma-ray bursts.

1 Introduction

Superluminal motion observed in active galactic nuclei (AGN), especially in the class of blazars, seems to be closely linked with high-energy emission. Such motion was recently observed in the Galaxy (Mirabel & Rodriguez, 1994, Hjellming & Rupen, 1995, Tingay, S. J., *et al.*, 1995) in the so-called microquasars. Nevertheless differences are underlined in those two cases. The latter systems were observed with small value of bulk Lorentz factor (around 2.5), while in the former ones values of about 10-20 are frequent. A possible acceleration mechanism is the so-called 'Compton rocket' effect (O'Dell, 1981), *i.e.* anisotropic inverse Compton effect on a highly relativistic plasma. It was then argued (Phinney , 1982) that because of Compton cooling, only small value of $\gamma_{b\infty}$ could be reached by this mechanism. However, in the frame of the 'two-flow' model (Sol, Pelletier & Asséo, 1989), a pair plasma can be reheated by the turbulence triggered by a surrounding jet (Henri & Pelletier, 1991) and then the Compton rocket can be more efficient (Marcowith *et*

al., 1995). We here describe more precisely our assumptions and present our main results on acceleration of such pair plasma.

2 Compton rocket effect with Klein-Nishina corrections

The pair plasma is assumed to be described by an energy distribution $n'_e(z, \gamma') \propto \gamma'^{-s}$ for $\gamma_{min} < \gamma' < \gamma_{max}$, with s , γ_{min} and γ_{max} independant on z . The radiation force is due to soft photon coming from a standard accretion disk (Shakura & Sunyaev, 1973) around a Schwarzschild black hole.

Let $\frac{dp'}{dt'}$ be the rate of momentum change for one electron and $\beta'c = \sqrt{1 - 1/\gamma'^2}c$ its velocity. The force exerted upon the pair plasma is then in the blob rest frame:

$$F'^z = \int d\Omega'_e d\gamma' n'_e(\gamma', \Omega'_e) \frac{dp'}{dt'} \cdot \mathbf{u}_z, \quad (1)$$

where \mathbf{u}_z defines the jet axis direction. To determine F'^z , one can use two different approximations: for low energy particules, the KN cross-section tends to the Thomson limit and we can apply the result of Phinney (1982) for an isotropic pair plasma. For high energy particules, KN corrections become important but we can assume that the head-on approximation is valid. In this approximation we determine both momentum and energy loss rates in the electron rest frame and rely them to the blob rest frame using Lorentz transformation (see Renaud & Henri, 1997, for detailed calculations.). We connect the two regimes by defining a critical Lorentz factor γ'_{crit} for which errors in the head-on approximation ($\gamma' > \gamma_{crit}$) and in the Thomson limit ($\gamma' < \gamma_{crit}$) are of same order. This gives $\gamma_{crit} \sim (2\langle\varepsilon\rangle)^{-1/3}$. $\langle\varepsilon\rangle \propto \dot{M}^{1/4} M^{-1/2}$, is the average photon energy emitted from accretion disk, \dot{M} is the accretion rate and M the mass of the central black hole. For AGN $\langle\varepsilon\rangle \sim 10^{-4}$ and $\gamma_{crit} \sim 20 - 30$ while for a microquasar $\langle\varepsilon\rangle \sim 10^{-2}$ and $\gamma_{crit} \sim 5$. Following Phinney (1982) we determine the acceleration of pair plasma by considering the conservation of stress-energy tensor. For a reheated relativistic plasma (with $p' = \rho'/3$) one finds the equation of motion.

$$\frac{d\gamma_b}{dz} = \frac{F'^z}{\rho'} \frac{1}{\frac{1}{3\gamma_b^2} + 1}, \quad (2)$$

3 Results

3.1 Effect of Klein-Nishina corrections

The effect of the KN corrections is to reduce the contribution of high energetic collisions in the net radiation force seen by the plasma. This leads to smaller value of terminal Lorentz factor than expected in the Thomson regime. KN corrections begin to dominate roughly when $\gamma_{max}\langle\varepsilon\rangle \sim 1$. The importance of this effect is so predominant for microquasars in which accretion disk radiates more energetic photons than in the extragalactic case.

3.2 Influence of the different parameters

We determine terminal Lorentz factor for different configurations: we consider the case of supermassive black holes $M = 10^9 M_\odot$ relevant to AGN and stellar black holes $M = 5M_\odot$ relevant to microquasars. For these two typical cases we show figure 1 the influence of the spectral index and the energy cut-off γ_{max} .

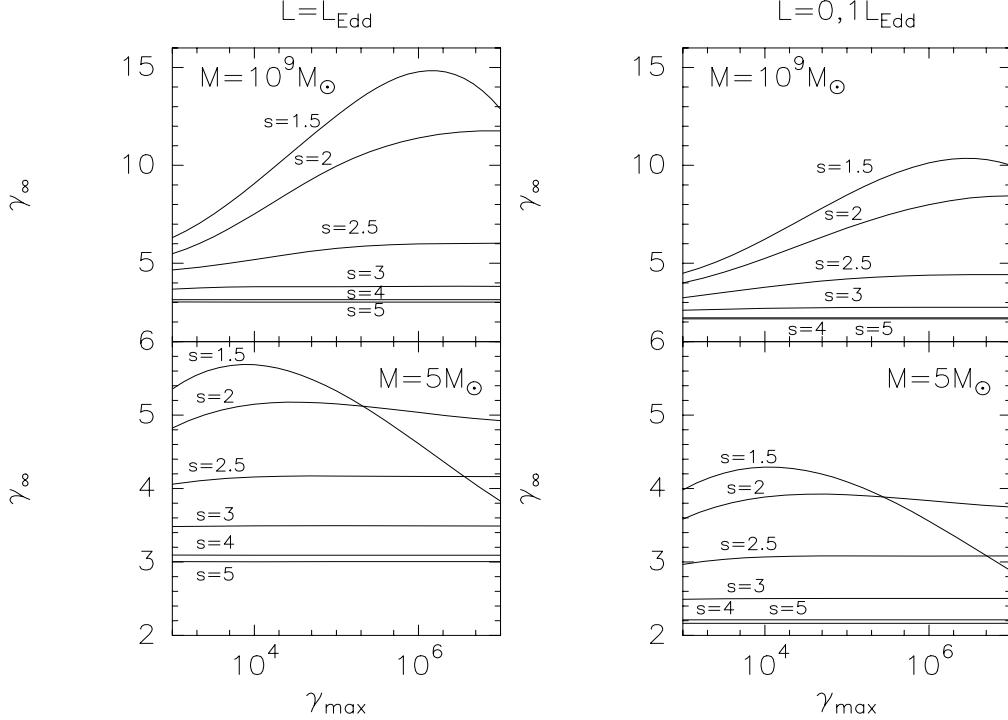


Fig. 1. Terminal Lorentz factor $\gamma_{b\infty}$ as a function of γ_{max} for different value of spectral index s . The two top pannels correspond to $M = 10^9 M_\odot$ black hole with $r_e = 3.10^3 r_g$, $L = L_{Edd}$ (left) and $L = 0.1L_{Edd}$ (right). The two bottom pannels correspond to $M = 5M_\odot$ black hole with $r_e = 3.10^3 r_g$, $L = L_{Edd}$ (left) and $L = 0.1L_{Edd}$ (right).

For $s < 3$, F'^z is dominated by the high value of γ' . Terminal Lorentz factor admits then a maximum when KN corrections begin to dominate. This value is more rapidly reached for a stellar black hole, explaining smaller $\gamma_{b\infty}$ than in extragalactic configurations. For $s > 3$, F'^z is dominated by the lower cut-off of the electronic distribution, explaining why no variation is evident with γ_{max} in this case (see Renaud & Henri, 1997). The plasma behaves as a cold one, and one finds small value of terminal Lorentz factor, like Phinney's result. The dependance on r_e is shown figure 2, where we extend the previous calculation to the case $r_e = 10r_G$. We find the same global behaviour of $\gamma_{b\infty}$ with spectral index and γ_{max} . In this configuration the radiation force is more efficient and $\gamma_{b\infty}$ can be as high as 60 in the extragalactic case.

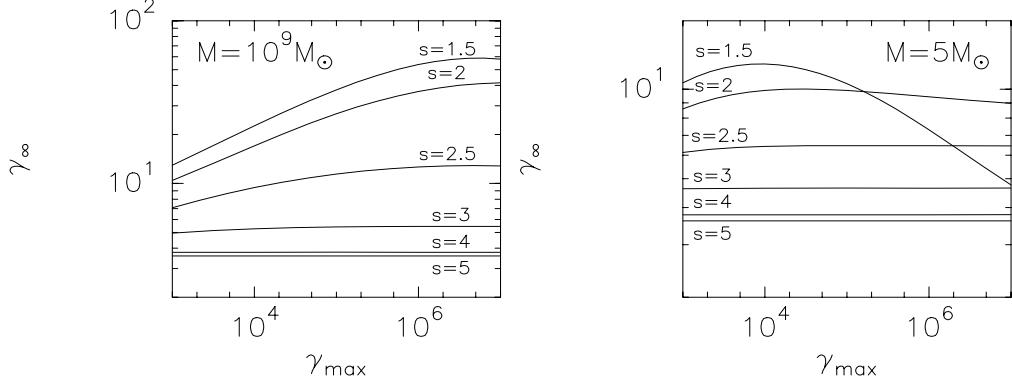


Fig. 2. Terminal Lorentz factor $\gamma_b \infty$ as a function of γ_{max} for different value of spectral index s . The two pannels correspond to $r_e = 10r_g$ and $L = L_{Edd}$, $M = 10^9 M_\odot$ (left) $M = 5 M_\odot$ (right).

4 Conclusion

We find that for a given luminosity, the terminal Lorentz factor $\gamma_b \infty$ admits a maximum due to KN corrections. They are predominant for stellar black holes leading to smaller values than for a supermassive black hole. Moreover the observed value of Lorentz factor of about 2.5 for the two microquasars with large spectral indexes (respectively $s \sim 4$, Finoguenov *et al.*, 1994 and $s \sim 4.6$, Harmon *et al.*, 1995) are coherent with our results. We also find that for fixed mass, spectral index, $\gamma_b \infty$ increases with decreasing r_e , reaching 60 for $r_e = 10r_g$, which is comparable to the value needed to explain observed flux in gamma-ray burst.

References

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